Thermo Electron Technologies Corporation



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# Blue Cesium Faraday and Voigt Filters

J. Menders, P. Searcy, K. Roff, S. Bloom, E. Korevaar
**Thermo Electron Technologies Corporation**
9550 Distribution Avenue
San Diego, CA 92121-2305
(619) 578-5885



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# ULTRA-NARROW MAGNETO-OPTIC ATOMIC LINE FILTERS FOR LASER RECEIVERS

- Background limited laser receivers require ultra-narrow linewidth filters to reach quantum limited operation
  - submarine laer communication
  - free space communication
  - remote sensing

- Like the conventional absorptive/re-emissive atomic line filters (ALF), the M-0 ALFs
  - operate at discrete atomic absorption lines
  - have Doppler limited passbands

- However, M-0 ALFs are imaging filters with
  - very high peak transmission
  - wide field-of-view
  - instantaneous response



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# TOPICS

- Principles of resonant magneto-optic filter operation
- Modelling approach to magneto-optic filters
- The Faraday and Voigt filters
- Setup for spectrum measurements
- Faraday filter spectra - measured and calculated
- Voigt filter spectra - measured and calculated
- Off axis transmission measurements and predictions at 455 nm
- The Faraday filter field-of-view

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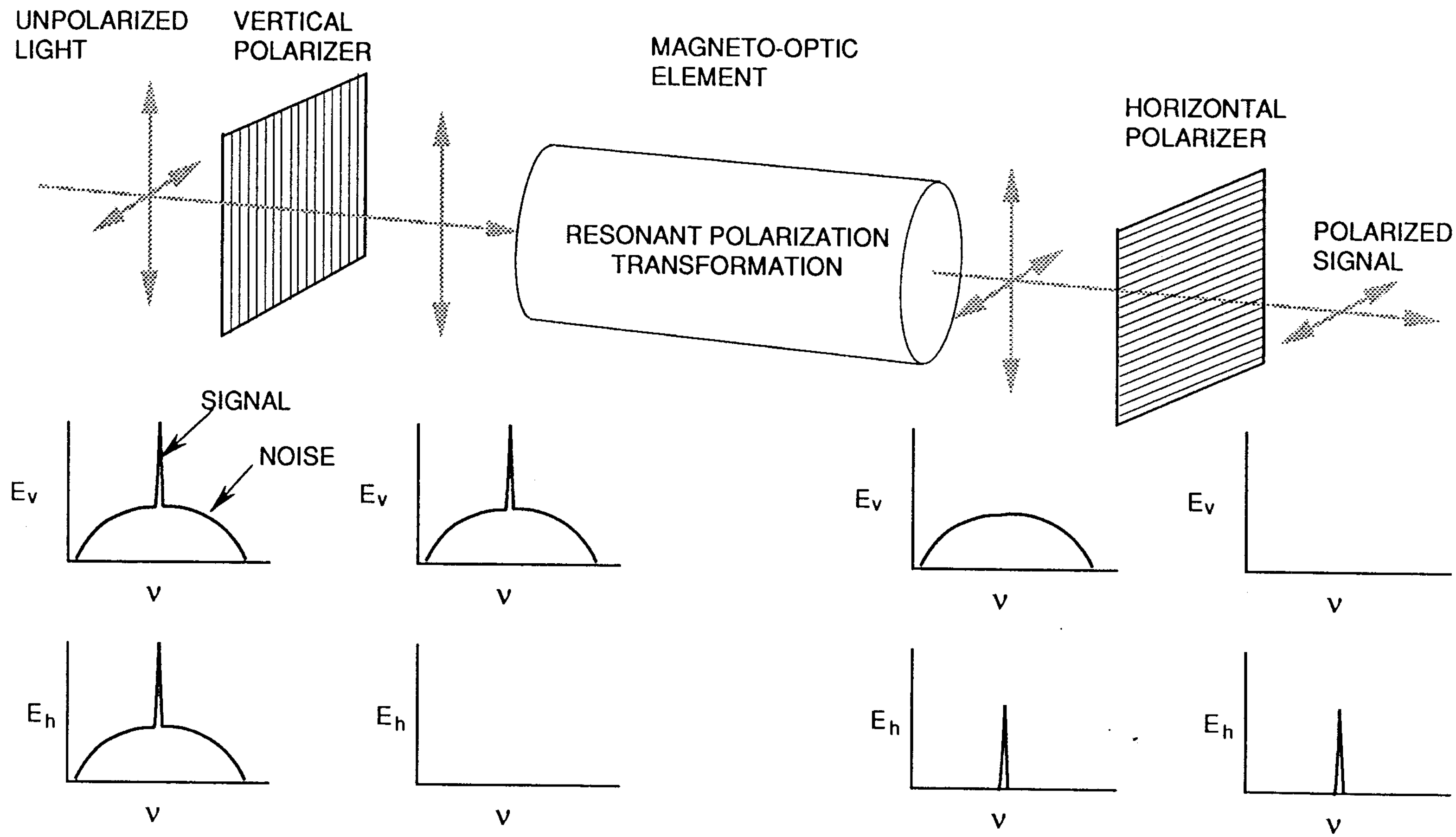
# PRINCIPLES OF RESONANT MAGNETO-OPTIC FILTER OPERATION




- The magneto-optic element transforms vertical into horizontal polarization over a narrow spectral band
- In-band light is transmitted; out-of-band light is blocked

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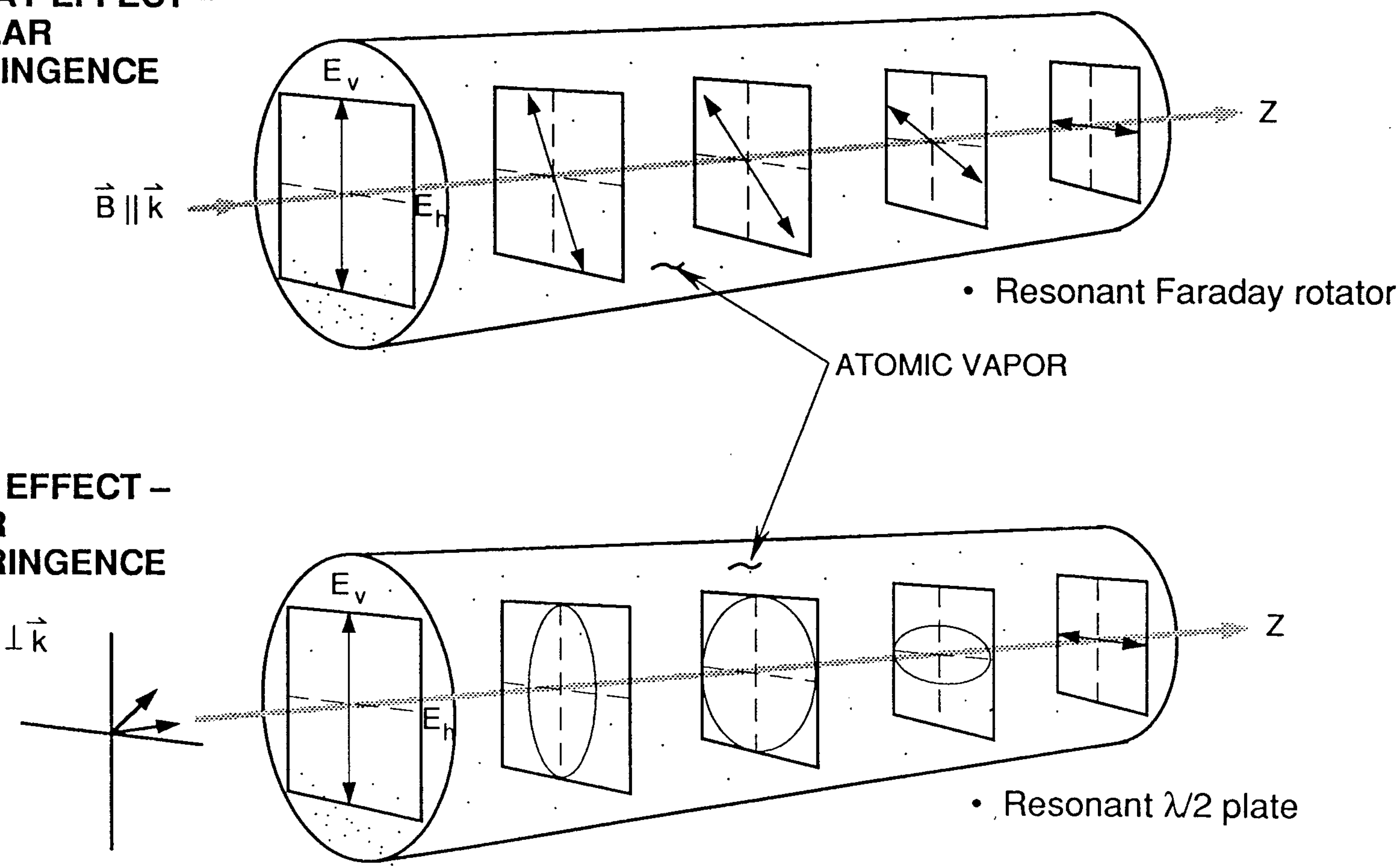
# FARADAY AND VOIGT EFFECTS IN ATOMIC VAPORS PROVIDE RESONANT MAGNETO-OPTIC ELEMENTS

**FARADAY EFFECT – CIRCULAR BIREFRINGENCE**

**VOIGT EFFECT – LINEAR BIREFRINGENCE**

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# FILTER TRANSMISSION SPECTRUM CALCULATION

## Atoms in a Magnetic Field

- Cs, $6^2 5_{1/2} \rightarrow 7^2\, p_{3/2}$, $\lambda = 455$ nm
- $H' =$ (hyperfine $\sim \vec{I} \cdot \vec{J}$) + (Zeeman $\sim \vec{B} \cdot \vec{J}$)
- $E_{FM_F}$ (B), $| FM_F >$
- $P_{ij} (\sigma_+)$, $P_{ij} (\sigma_-)$, $P_{ij} (\pi)$

## Vapor Optical Coefficients

- N (T), $g_D$ (v)
- $\alpha (\sigma_+)$, $\alpha (\sigma_-)$, $\alpha (\pi)$
- $\alpha (\sigma_+)$, $\alpha (\sigma_-)$, $\alpha (\pi)$

## Propagation Eigen Modes

- $n_i (\vec{k})$, $\vec{\varepsilon}_i (\vec{k})$

## Transmission Spectrum

- $\vec{E}(z) \sim \hat{\varepsilon}_1 E_1 (o)\, e^{i(n_1 k_o z)} + \hat{\varepsilon}_2 E_2 (o)\, e^{i(n_2 k_o z)}$

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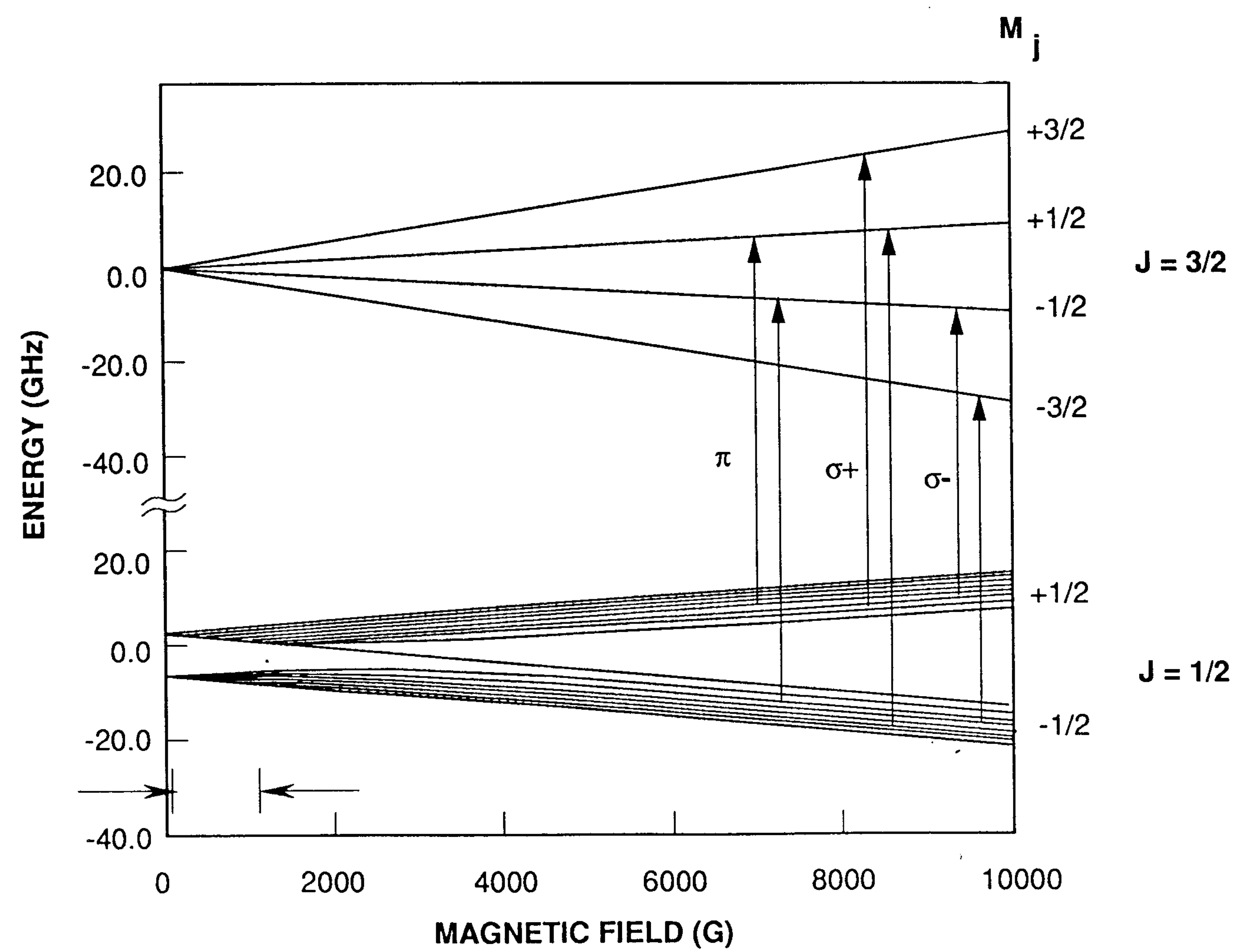
# Cs $6s_{1/2}$ - $7p_{3/2}$ (455 nm)
# HYPERFINE AND ZEEMAN SPLITTING

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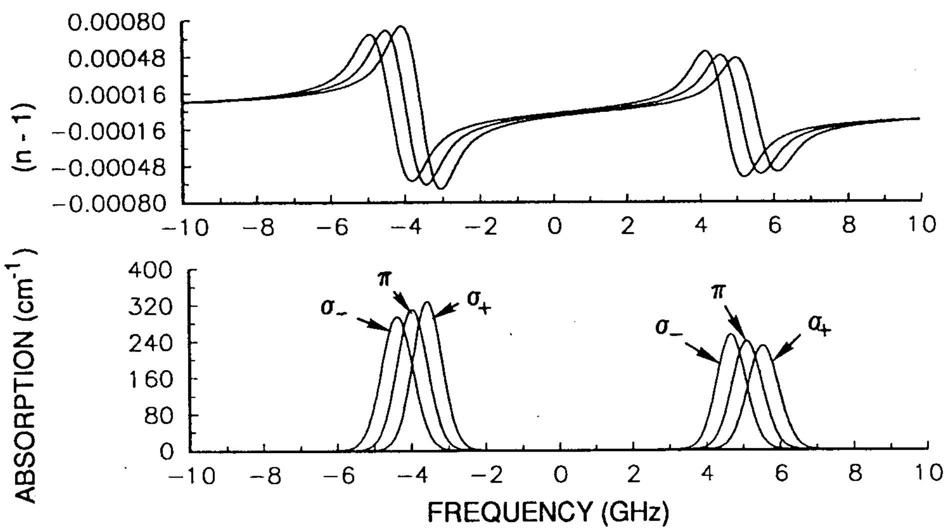
# REFRACTIVE INDICES AND ABSORPTION

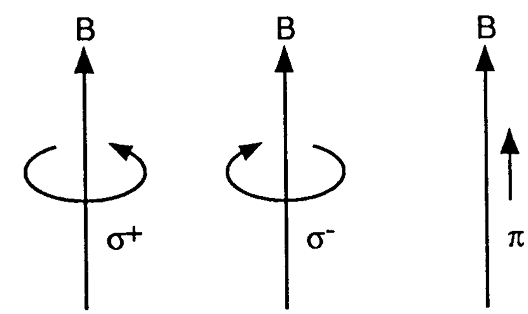



Cs, 455 nm

T = 200° C

B = 200 G

L = 1 in.

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## THE LEFT- AND RIGHT CIRCULAR POLARIZATION ANALYSIS IS SPECIFIC TO PROPAGATION ALONG $\vec{B}$

- In general, other directions have varying eigen-polarizations and -indices
- A simple dielectric tensor w.r.t. the $\hat{R}, \hat{L}, z$ basis describes the Faraday effect for a field along z

$$\varepsilon = \begin{bmatrix} \varepsilon_0 & -i\cdot\varepsilon_B & 0 \\ +i\cdot\varepsilon_B & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{bmatrix}$$

where $\varepsilon_o = n_z^2$ and $\varepsilon_B = n_r^2\ n_l^2$

- Maxwell's equations lead to a matrix form of the wave equation

$$\left\{ \varepsilon_i \cdot \begin{bmatrix} -s_y^2 - s_z^2 & s_x \cdot s_y & s_x \cdot s_z \\ s_x \cdot s_y & -s_x^2 - s_z^2 & s_y \cdot s_z \\ s_x \cdot s_z & s_y \cdot s_z & -s_x^2 - s_y^2 \end{bmatrix} + [\varepsilon] \right\} \vec{E} = 0. \quad \vec{k} = |\vec{k}|\,\hat{s}$$

- Eigen - indices $n_i^2 = \varepsilon_i$ are determined from $|\{\ldots\}| = 0$.

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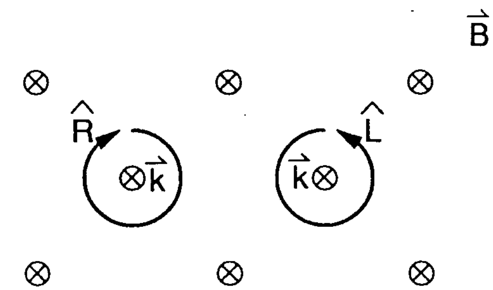
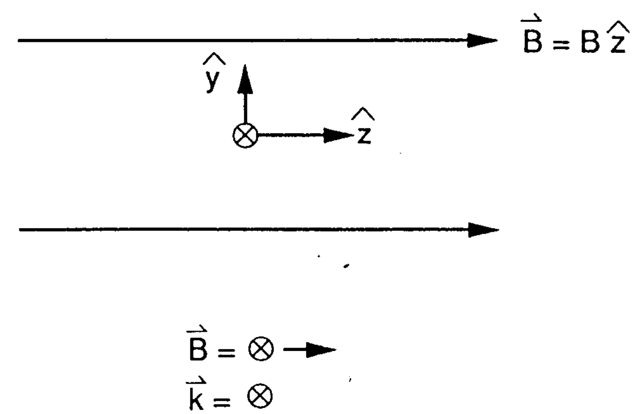
# TWO PROPAGATION DIRECTIONS YIELD SIMPLE EIGEN INDICES AND POLARIZATIONS

- Propagation along $\vec{B}$ (Faraday Effect)
  - Circular polarizations $\hat{R}$, $\hat{L}$
  - Circular indices $n_R$, $n_L$




- Propagation perpendicular to $\vec{B}$ (Voigt effect)
  - Linear polarizations $\hat{y}$, $\hat{z}$
  - $n_y = \frac{1}{2}(n_R + n_L)$; $n_z = n_\pi$
  - Similar to birefringence

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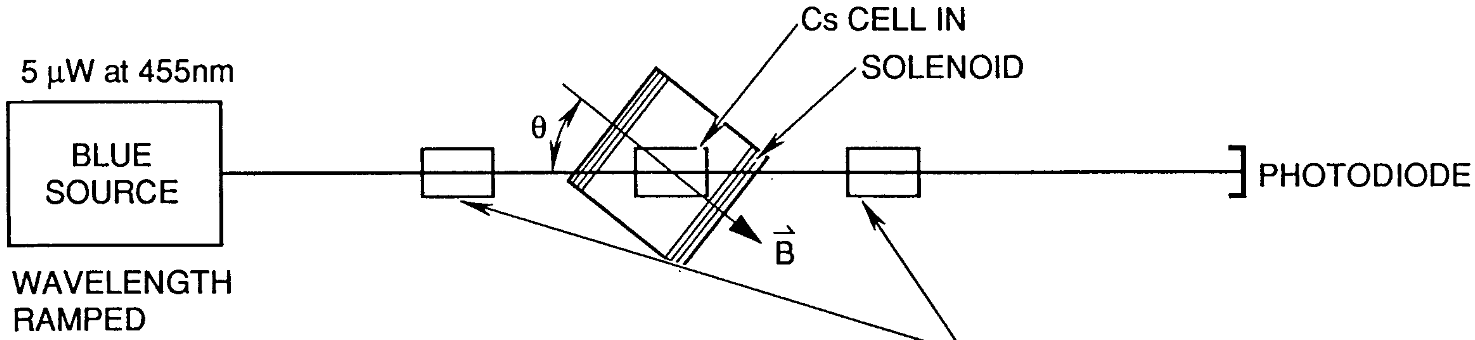
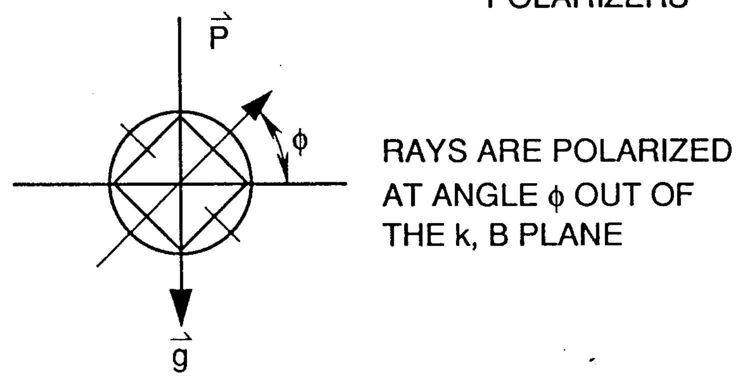
# OFF-AXIS TRANSMISSION EXPERIMENTS




- Beam's eye view of the front polarizer




- This cell and field arrangement avoids the complication of variations in Fresnel losses
- Transmission spectra do not reflect pathlength increases with θ

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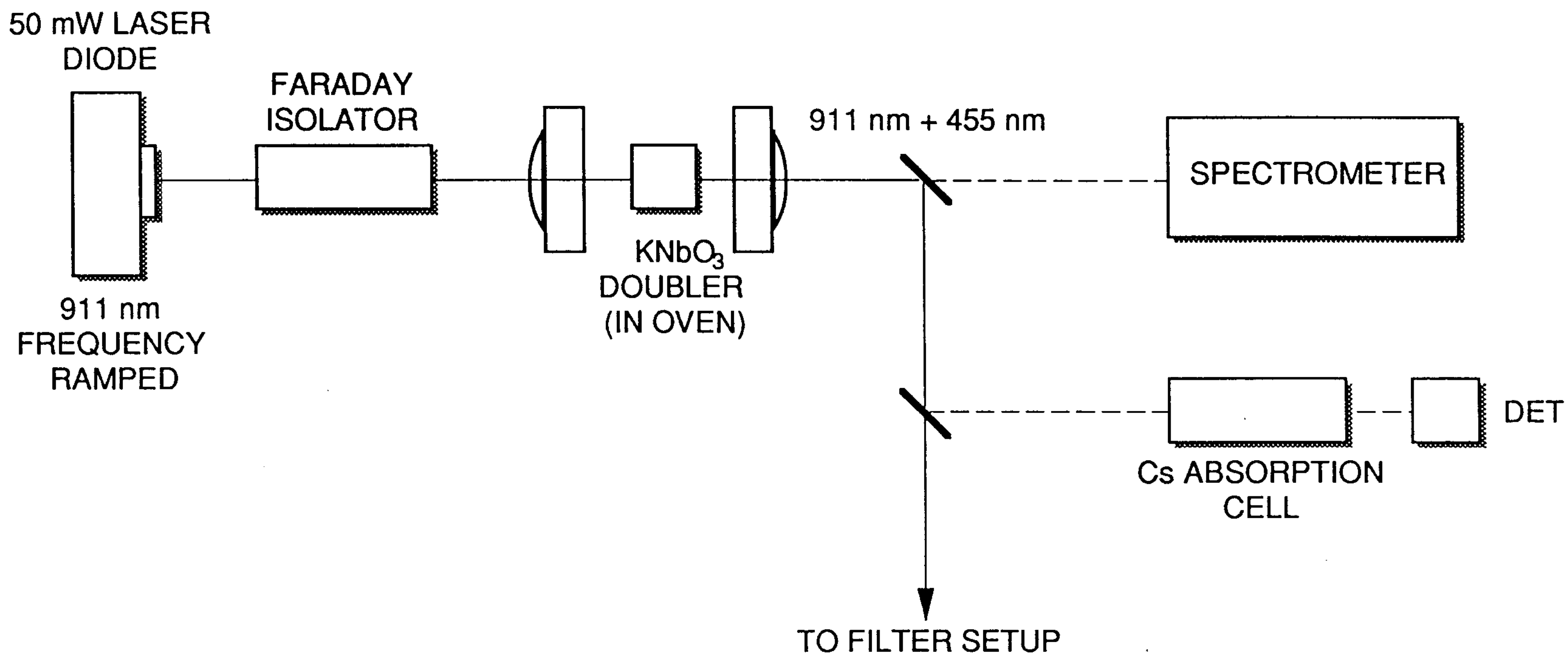
# BLUE SOURCE

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# FILTER TRANSMISSION MEASUREMENT SET-UP

- The beam and the cell remain fixed
- The solenoid rotates to set $\theta$
- Crossed polarizers "roll" to set Ø

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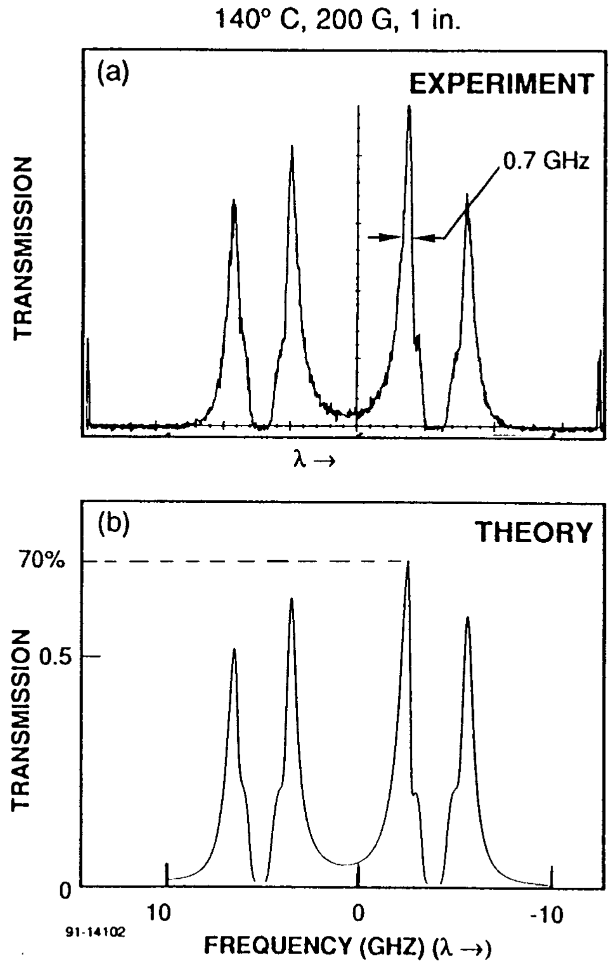
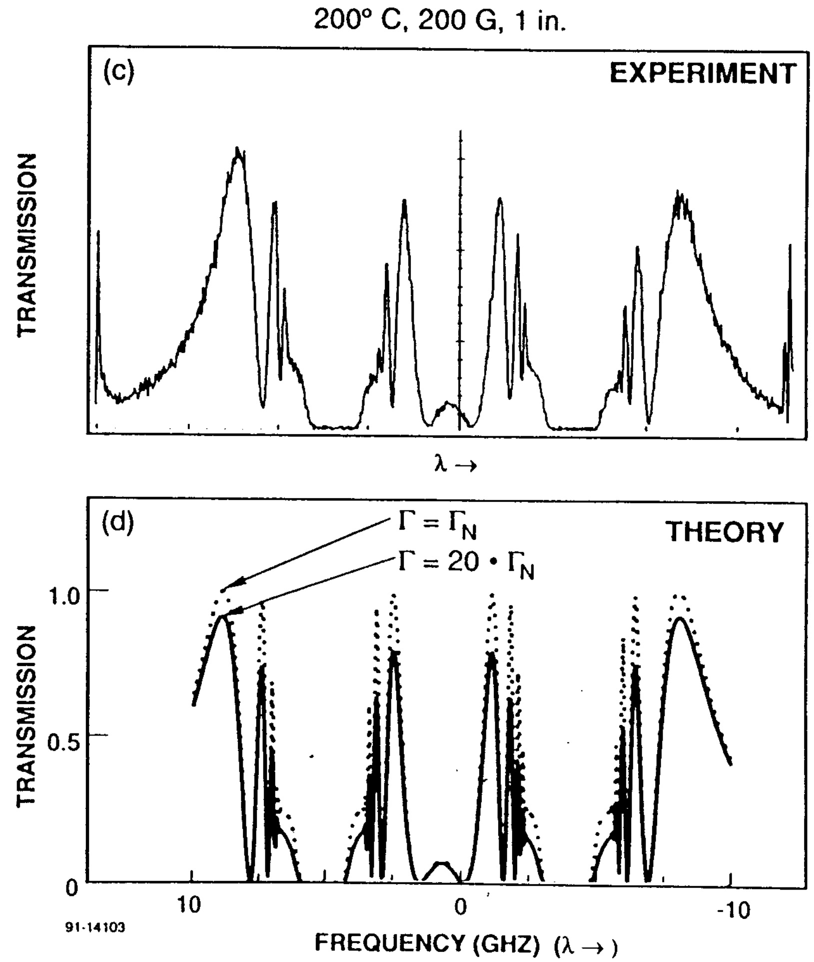
# BLUE FARADAY FILTER ( $\vec{k} \parallel \vec{B}$ ) SPECTRA ARE WELL PREDICTED




- Optimum conditions minimize bandwidth and maximize transmission
- Additional broadening becomes apparent at temperature $T \geq 200°$ C

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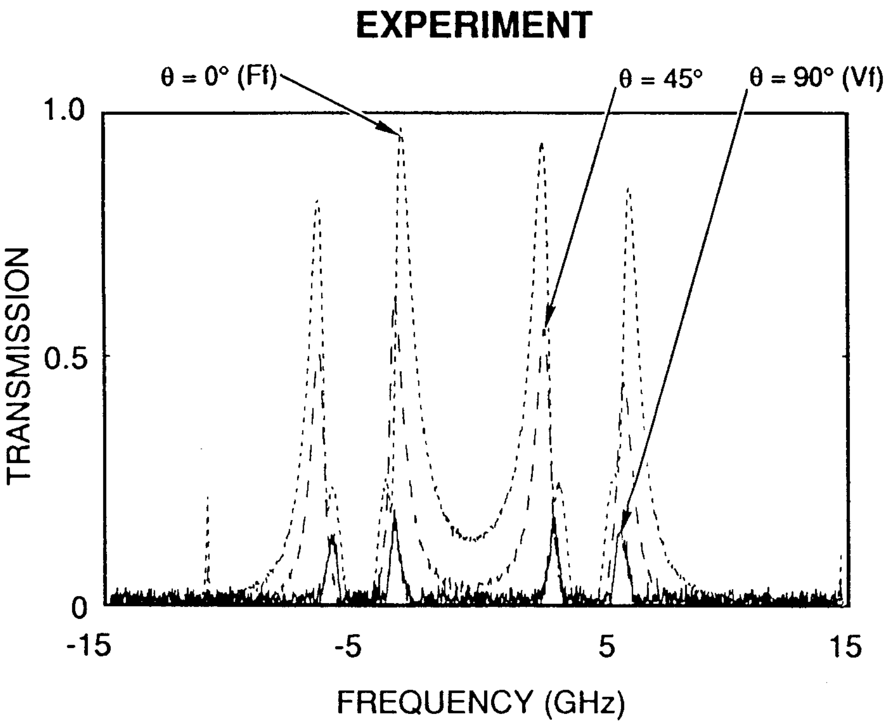
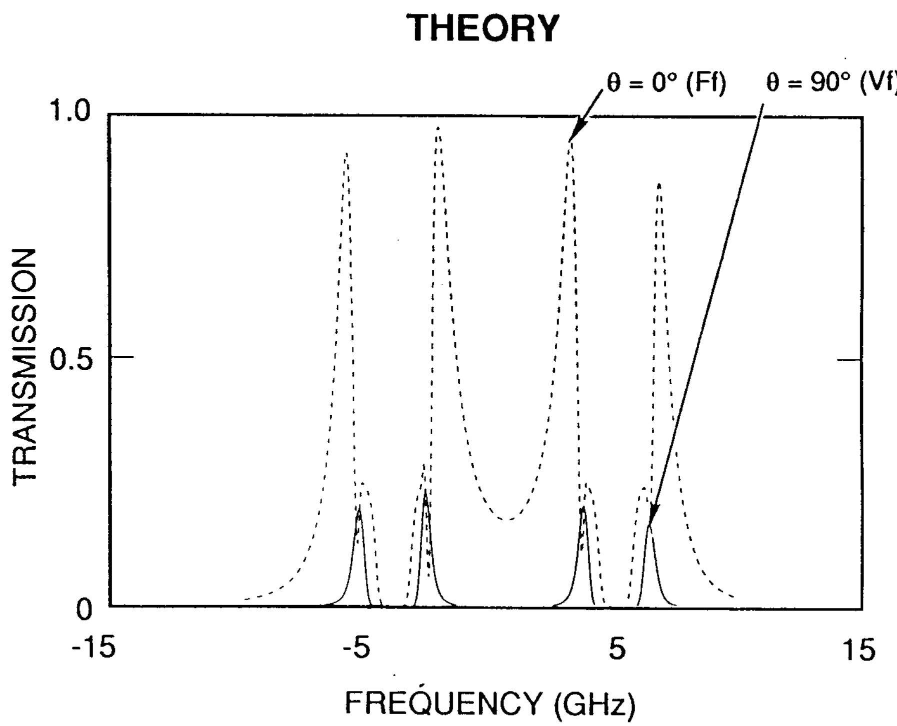
# BLUE FILTER TRANSMISSION vs. $\theta$ AT $\phi = 45°$




**Cs, 455 nm with T = 140° C, B = 200 G, L = 1 in.**

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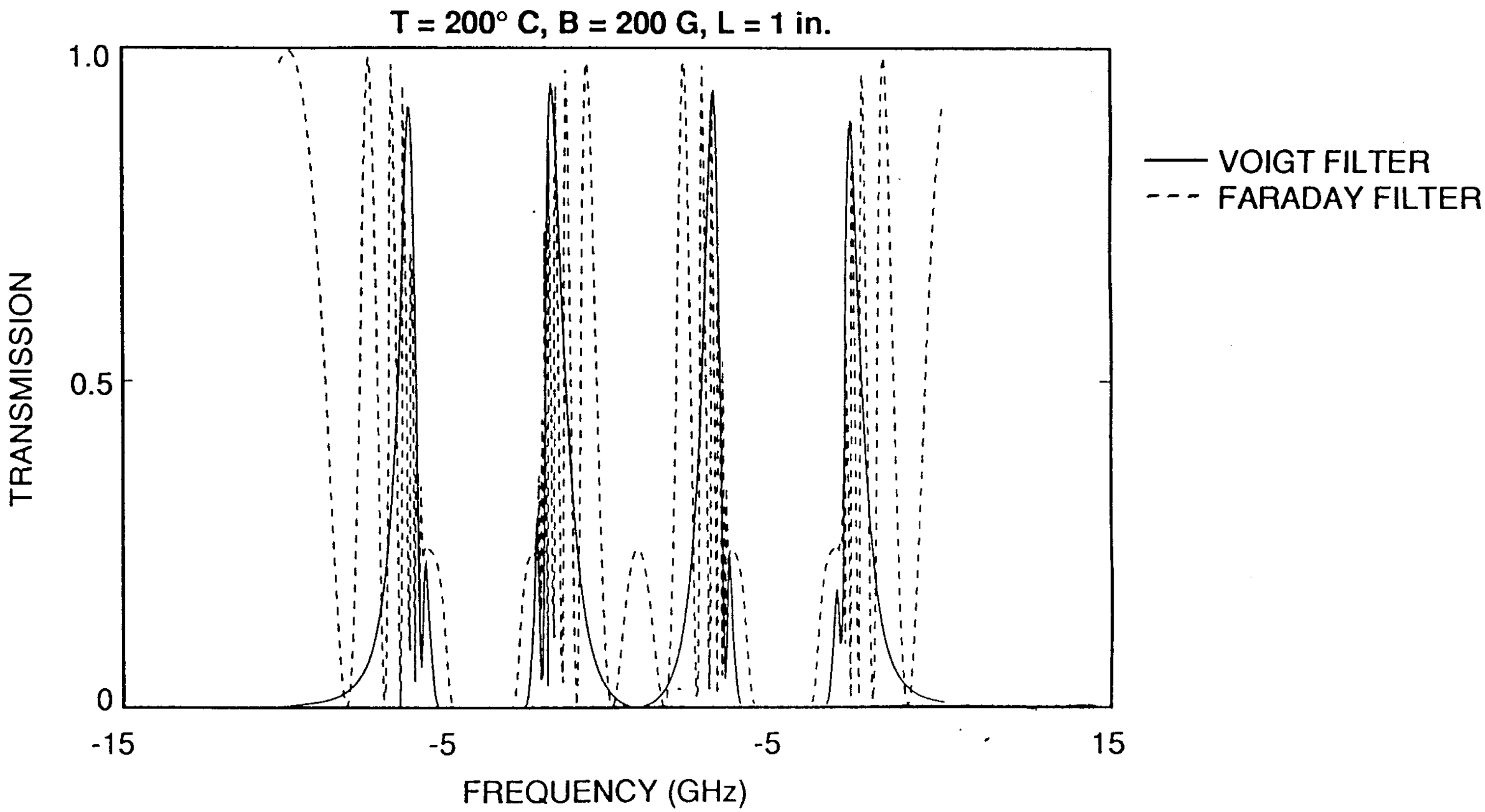
# OPTIMIZED VOIGT FILTER CALCULATION




- High transmission (15%) and narrow bandwidth (0.6 GHz)
- The optimum Voigt filter transmission spectrum occurs at a higher temperature than the optimum Faraday filter spectrum

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## BLUE FARADAY FILTER FIELD-OF-VIEW ASSESSMENT

- A heuristic argument led to wide FOV expectations:

  since $Z = \frac{L}{\cos\theta}$ and $\Delta n \propto \vec{B} \cdot \vec{k} = B\,k\cos\theta$, we expect $z\Delta n \sim$ const

- Approach to FOV assessment
  - Anchor off-axis modelling to experiments
    -- z fixed in experiments
  - Calculate FOV ($z = L/\cos\theta$)

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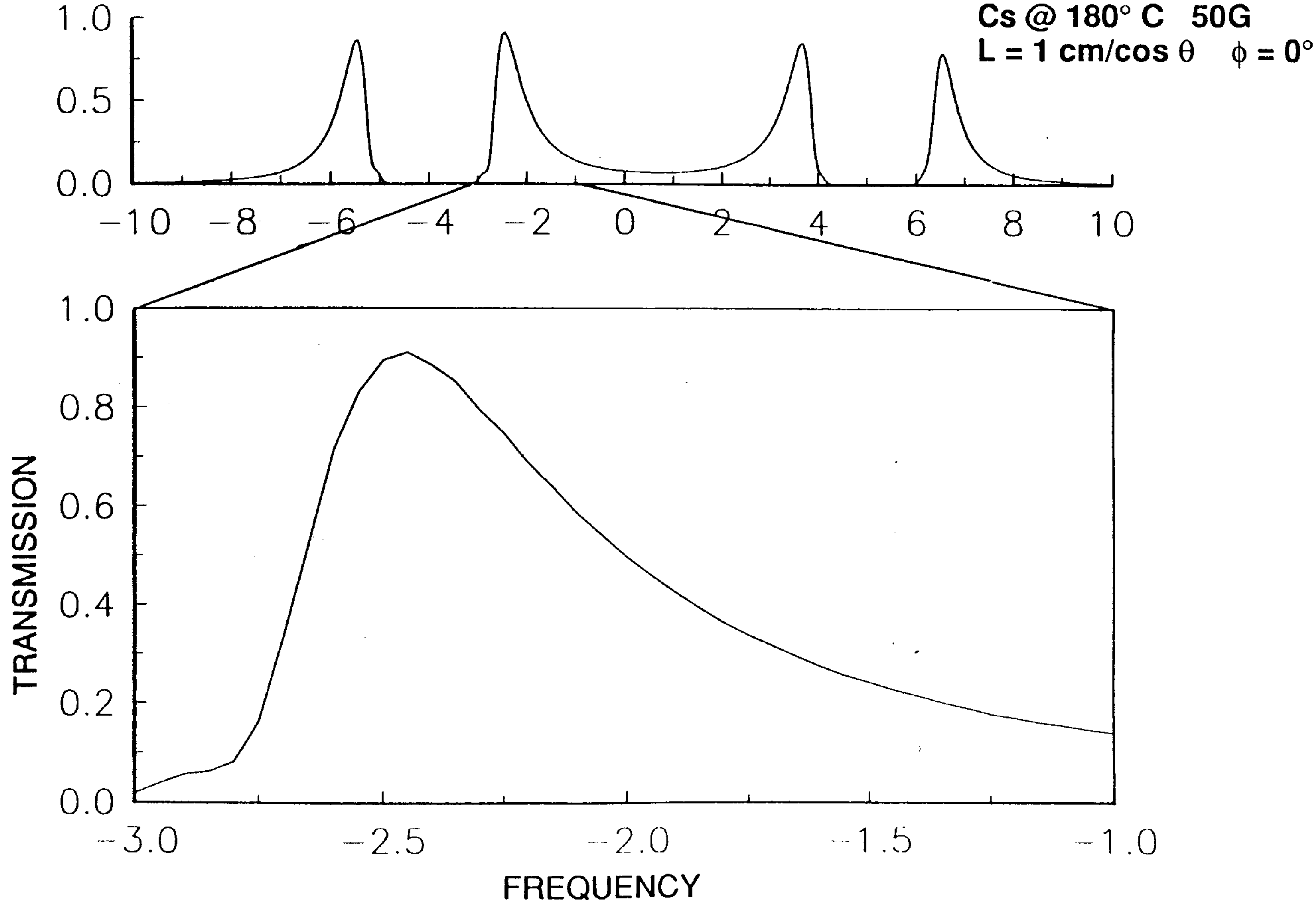
# WE HAVE ANALYZED THE SENSITIVITY OF A TYPICAL BLUE PASSBAND IN DETAIL

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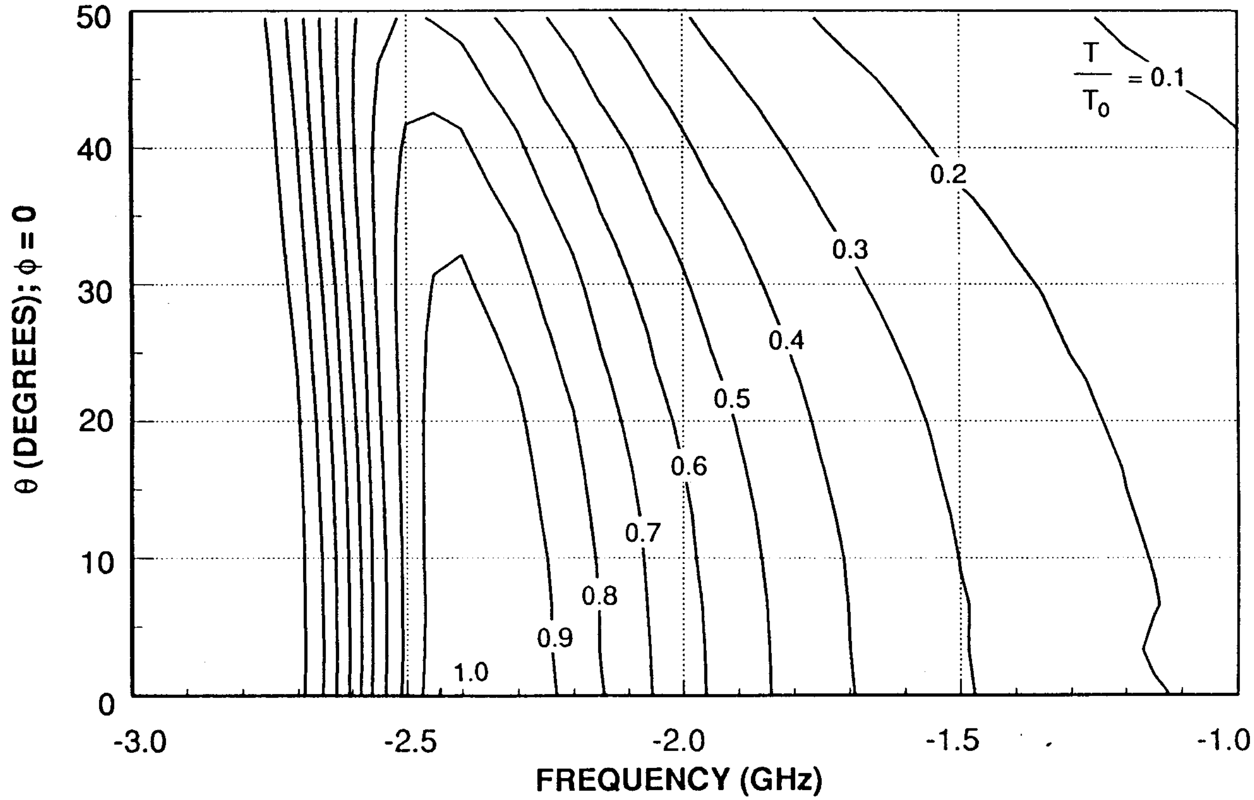
# NORMALIZED TRANSMISSION SPECTRA CONTOURS OVER FIELD ANGLE FOR A PASSBAND NEAR 455 nm




- Faraday filter operated at 180° C, 50 G, 1 cm
- Horizontal slices give spectra at fixed angle
  — Passband position is independent of angle
- Vertical slices give T vs. $\theta$
  – Peak transmission decreases by 10% for $\theta = 31°$

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## CONCLUSIONS

- Ultra-narrowband blue Faraday and Voigt filter spectra have been observed
  - Spectra agree with our predictions
  - Near unity transmission
  - ~ 1 GHz passbands
  - 3 GHz integrated transmission

- We predicted and observed a new type of ultra-narrowband filter - the "Voigt filter"
  - Transverse magnet geometries may lead to higher packing densities

- A typical blue Faraday filter passband is insensitive to field angles up to 35°